

Capacitor & Amplifier Distortions

Cyril Bateman uses his real-time distortion measuring system to investigate capacitor distortions in audio power amplifiers

Assembled using polar aluminium electrolytic capacitors for C1, 3, 9 and 11, my workhorse 100 watt Maplin Mosfet amplifier, tested at 1kHz and 25 watts into an 8 Ω load, measured -81.5dB second harmonic, -91.4dB third harmonic, clearly meeting its claimed less than 0.01% distortion¹. **Fig. 1.**

Replacing the four polar aluminium electrolytic capacitors in this schematic, with the same value and voltage rating bi-polar electrolytics and no other changes, amplifier distortion improved dramatically, becoming -92.1dB second and -94.3dB third harmonic, re-measured a few minutes later. This article is

based on more than eighty distortion measurements, taken while investigating the possible reasons for these improvements.

In the past, many amplifier designers have stated that provided the capacitance value is chosen to ensure only a small AC signal voltage drop can appear across capacitors at the lowest frequencies, then capacitor distortion can be ignored.

My original *Capacitor Sounds* series² found measurable distortions occurring in un-biased polar aluminium electrolytic capacitors tested at 0.1 volt AC, my smallest practical test voltage. With signals this small, second harmonic of the lowest distortion 100 μ F 25 volt DC

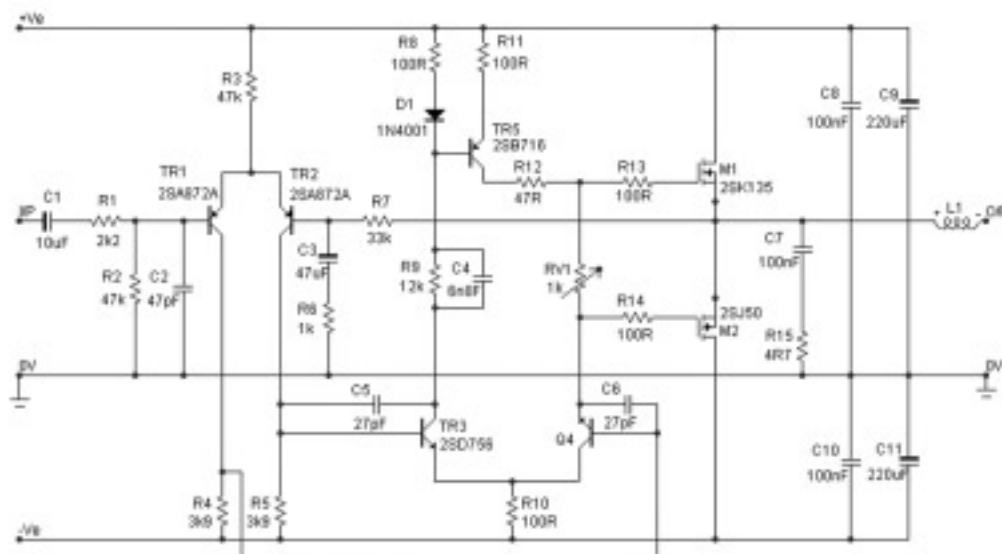
rated polar capacitor I tested, measured -99.5dB with 6 volt bias and -94.4dB with 12 volt bias. Using 0.2 volt AC and larger test voltages, second and third harmonic distortions in polar aluminium electrolytic capacitors increase dramatically, measured with and without DC bias voltage.

Tested using a 1 volt signal, this capacitor's third harmonic remained close to -100dB, with no bias its second harmonic was -93.2dB, increasing to -77.9dB at 6 volt bias and -72.9dB with 12 volt bias. Application of a very small, optimal bias, typically less than 3 volts DC, to selected capacitors may minimise the second harmonic, however for every electrolytic capacitor I tested, further increase of bias voltage resulted in increased second harmonic distortion.

Contrary to the popular belief that a polar aluminium electrolytic capacitor should be biased to 50% rated voltage for minimal distortion, my measurements show that second harmonic distortion can only be minimised by using very small or no DC bias. Any further increase in DC bias increases the second harmonic generated by the capacitor. Application of DC bias at 50% of the capacitor's rated voltage as shown in the figure, results in exceptionally large second harmonic distortions, even for this, the lowest distortion, the best polar capacitor, of those measured. **Fig. 2.**

At very low frequencies, as capacitor impedance increases, signal

Fig. 1. Schematic circuit of my Maplin Mosfet 100W amplifier, redrawn for convenience using my Microcap MC6 circuit simulator.



voltages could occur in the circuit sufficient to generate measurably increased distortion. However at my 1kHz distortion measurement frequency, all four capacitors have low impedance, so are subject only to small AC signal voltage drops, apparently not sufficient to explain my measured reduction in distortion when replaced by the same value and voltage bi-polar types.

At a given test frequency, capacitor distortions do vary with capacitor AC signal levels and DC bias voltage, but for my Maplin amplifier comparison tests, nominal capacitance values were unchanged so both sets of polar and bi-polar capacitors experienced the same signal voltages. Why should simply changing these capacitors from polar to bi-polar types, provide such benefit?

Capacitor C3 conditions

I ran a few simulations to identify the capacitor most likely to influence this amplifier's distortion. As in many power amplifiers, a 47µF polar aluminium electrolytic capacitor, C3, is used in the feedback network, to roll off amplifier gain at low frequencies, minimising DC offset at its output. With 33kΩ for R7 and 1kΩ for R6, this capacitor is presented with a high impedance for charge and discharge currents. My original *Capacitor Sounds* measurements used lower impedances. Might this high impedance condition affect the capacitor's distortion contributions?

It seemed possible that distortions generated in the capacitor result from two mechanisms, a current dependant component in addition to the voltage component already identified. Throughout that series, I related distortions measured in capacitors to their signal and bias voltages, using test circuit source impedance some two thirds that of the capacitor's at 1kHz for values to 1µF, 100Hz for 1µF and larger values.

I expected to find some third harmonic current dependency from non-ohmic resistances in the capacitor internal connections. Second harmonic distortions in capacitors result from dielectric absorption effects, DC bias and test voltage level, so I wondered whether a change of measuring current with constant bias and test voltage, would reveal changes also in the second harmonic?

In my original *Capacitor Sounds* series I described test equipment designed and built to measure capacitor distortion at 100Hz and 1kHz. For another project last year I

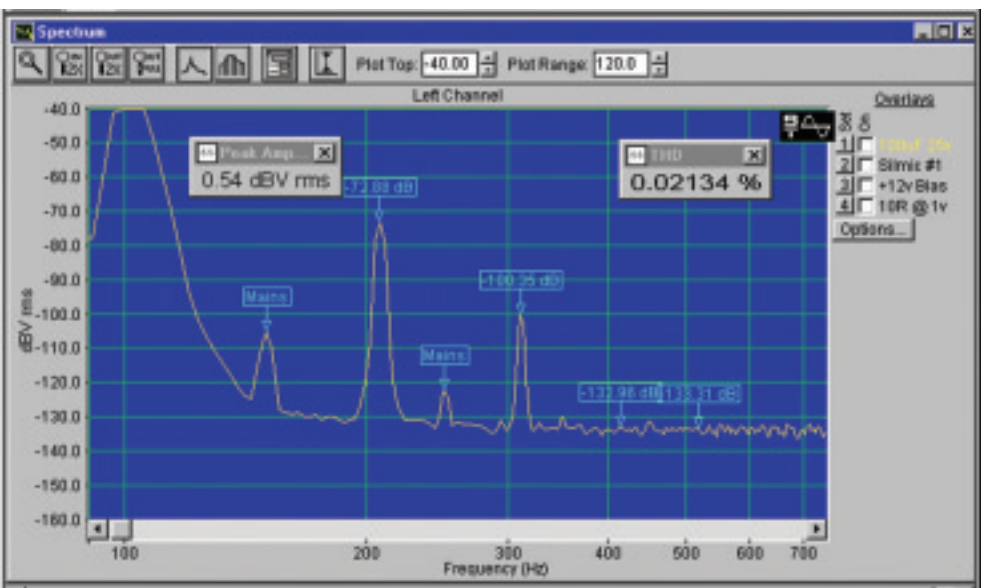


Fig. 2. Distortion results for a Silmic 100µF 25 volt rated polar aluminium electrolytic capacitor, with 12 volt DC bias and tested using 10Ω source impedance generating 1 volt across the capacitor. With no bias, second harmonic distortion for this capacitor was -93.2dB and -77.9dB with 6 volt bias.

assembled a 5kHz test oscillator, buffer amplifier, notch filter/preamplifier, using 1kHz PCBs with smaller tuning and filter capacitors.

Following a few tests, I found this equipment could develop an undistorted 0.5 volt 5kHz signal across my 1µF FKP reference capacitor using 100Ω source impedance. I could measure distortions produced by a 1µF polar aluminium electrolytic capacitor at three test frequencies, 100Hz, 1kHz and 5kHz, using 100Ω source impedance, increasing capacitor test current from 314µA at 100Hz to 15.7mA at 5kHz at constant test voltage. Perhaps that would clarify any capacitor current dependant component.

Using 100Ω source impedance and no bias, I adjusted test levels to develop a 0.5 volt AC voltage across the capacitor at each frequency. Second harmonic distortion increased by 8dB and third harmonic 4.3dB with this change of capacitor current. Clearly both second and third harmonic distortions do increase with capacitor current and AC voltage drop.

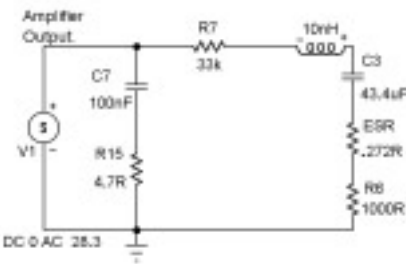


Fig. 3. To simplify my simulations, I extracted the C3 and C7 capacitor sub circuits from the Figure 1 schematic and used the amplifier output voltage as my calculation stimulus. Much simpler, quicker and less prone to simulation errors than when modelling the amplifier.

Second harmonic distortion increases rapidly with DC bias voltage.

Circuit conditions

A few simulation runs using measured capacitance and ESR values by frequency, would establish the voltage and current for capacitor C3, from 10Hz to 20kHz and beyond. Analogue behavioural modelling techniques could be used, but determining the capacitor model can be time consuming and many readers may not have a suitable simulator. Far simpler and quicker - make several frequency runs using measured values for a specific frequency in turn, noting the result for that frequency. This method is practical using the simplest simulator.

Table 1: With 0.5 volt AC test voltage, 100Ω source impedance and no bias, I found second and third harmonic distortion increasing with capacitor current. Clearly both second and third harmonic distortions do increase with capacitor current, voltage drop and second harmonic with DC bias.

Frequency	Impedance	Test Current	Second Harmonic	Third Harmonic	% T.H.D.
100Hz	100Ω	314µA	-107.8dB	-115.7dB	0.00047%
1kHz	100Ω	3.14mA	-102.4dB	-111.6dB	0.00083%
5kHz	100Ω	15.7mA	-99.8dB	-111.4dB	0.00117%

Table 2: Measured values of a 47 μ F 50 volt Panasonic ‘S’ bi-polar aluminium electrolytic capacitor as used for C3, with results from my eight simulation runs

Measured Values.				Simulation Results.	
Frequency	Capacitance	Actual ESR	Impedance.	Voltage drop	C3 Current
10Hz	49.08μF	25.74Ω	325.29Ω	270.82mV	832.0μA
20Hz	48.54μF	12.97Ω	164.52Ω	138.02mV	832.03μA
100Hz	45.41μF	1.862Ω	35.09Ω	29.28mV	832.31μA
300Hz	44.24μF	0.575Ω	12.01Ω	10.07mV	832.33μA
1kHz	43.40μF	0.272Ω	3.67Ω	3.05mV	832.35μA
3kHz	42.74μF	0.210Ω	1.26Ω	1.05mV	832.35μA
10kHz	41.71μF	0.191Ω	0.426Ω	0.35mV	832.35μA
30kHz	40.00μF	0.182Ω	0.225Ω	0.18mV	832.35μA

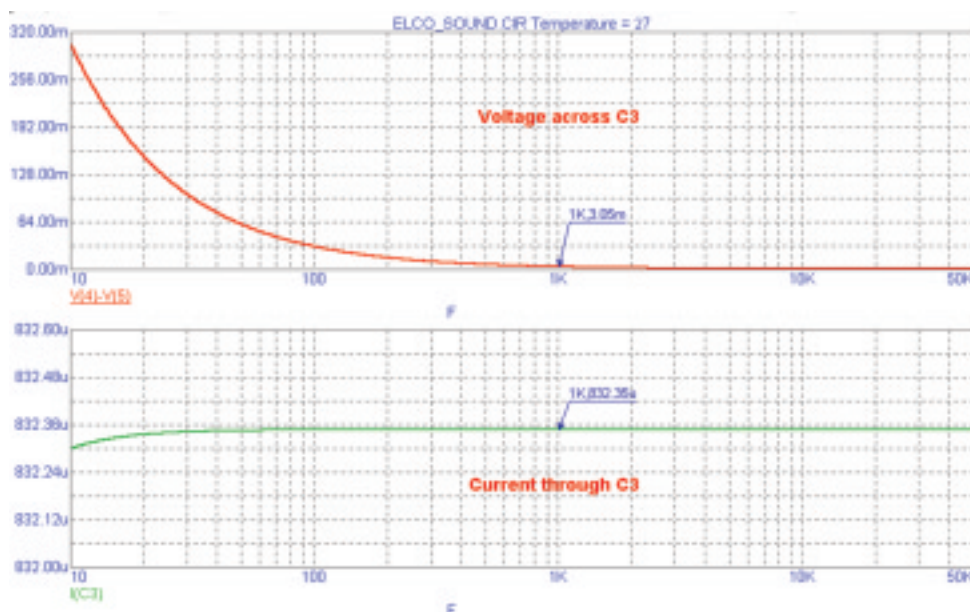


Fig. 4. One of eight simulations needed to accommodate C3 measured parameters by frequency, showing the 1kHz results. Voltage across C3 reduces with frequency but current through C3 remains almost constant regardless of frequency.

I extracted the feedback resistor network with this capacitor from the main circuit and used the amplifier's output voltage for 100 watt into 8Ω as the stimulus. I measured a radial lead, $47\mu\text{F}$ 50 volt Panasonic 'S' bipolar electrolytic, the type used when exchanging the capacitors, for capacitance and ESR by frequency. Self resonance was 300kHz, so estimating 10nH for its self inductance, typical of many radial lead aluminium electrolytics in a $20 \times 10\text{mm}$ case, completed the model. **Fig. 3.**

Using my Hewlett Packard reference test jig and Wayne Kerr B6425 precision digital LCR meter, I measured this capacitor from 10Hz to 30kHz, for capacitance value and ESR. These pairs of values were inserted into the model in turn for each of eight simulation runs, noting the voltage drop across the capacitor model, from the negative side of the 10nH to the junction of ESR and R6, also C3 through current.

For each run, similar voltage and current plots were observed with subtle changes at the frequency of interest, for the capacitor parameters used. Clearly capacitor signal voltage does reduce with increasing frequency but capacitor current remains almost constant, generating a near constant level of current dependant distortion. **Fig. 4**

Protection Diodes

Most published amplifiers using a polar aluminium electrolytic capacitor for this C3 position add a diode or pair of diodes in parallel, to

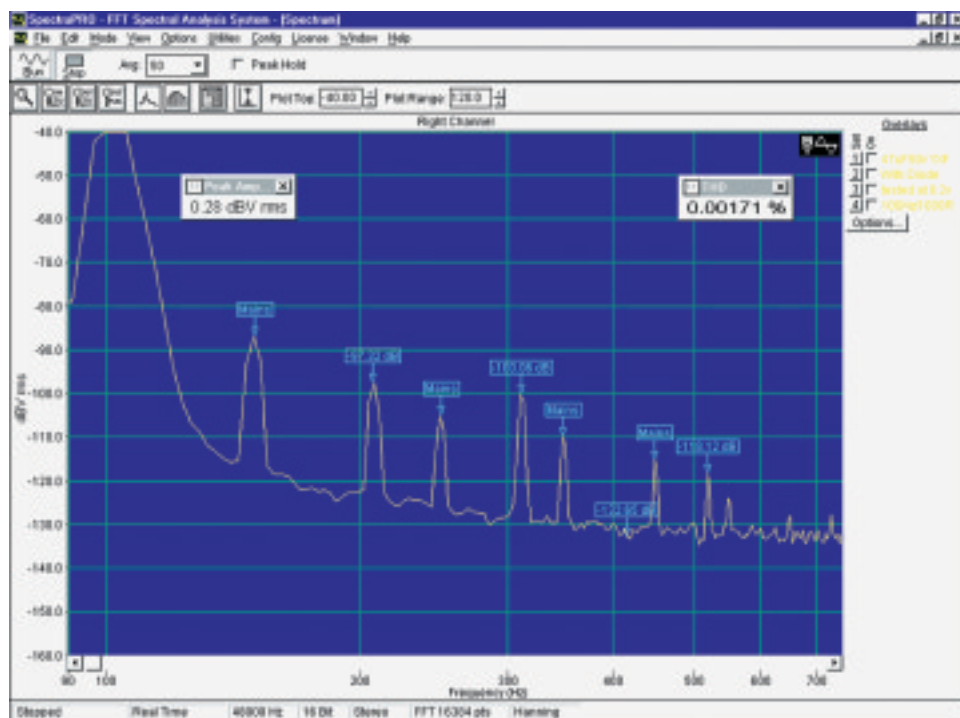


Fig. 5. A Rubycon YXF 47 μ F 25 volt rated polar aluminium electrolytic capacitor tested at 100Hz and 200mV with diodes. Without diodes, third harmonic was -122.67dB, a more than 20dB improvement. At this test voltage, low level AC mains harmonics cannot be eliminated, for clarity test frequency was 103.8 Hz and mains peaks labelled.

protect the capacitor should the amplifier 'go DC' with its output voltage 'stuck' to a supply rail. It has often been claimed such diodes do not distort at the capacitor's signal voltage levels, but I wondered if that were correct. Using a pair of 1N4448 diodes and my 1 μ F FKP reference capacitor, I made measurements at 1kHz with 100 Ω source impedance and test voltages of 75mV, 100mV, 150mV and 200mV, comparing distortion results with and without diodes.

Measured with diodes, third harmonic distortion was visible at -110dB for the 75mV test, increasing to -100dB for 100mV and -84.9dB tested at 200mV, when a fifth harmonic at -100dB was seen. These harmonics result from the diodes conducting slightly at these test voltages since without diodes, my FKP reference capacitor was distortion free.

I measured distortions at 100Hz, with and without diodes, for a variety of 47 μ F and 100 μ F polar aluminium electrolytic capacitors, rated at 25 volt and 50 volt, comparing these results with those for the same value bi-polar electrolytics. The results were overwhelmingly conclusive. At 200mV with diodes, third harmonic distortion increased by 20dB with polar and bi-polar capacitors. At 100mV I found smaller increases of third harmonic, depending on the level of distortion generated by the capacitor without diodes. Tested at 0.1 volt with diodes, this capacitor generated -96.8dB second and -108.2dB third harmonic distortion.

Fig. 5.

I question whether these protection diodes are necessary for polar aluminium electrolytic capacitors in this circuit. They certainly are not needed using a bi-polar aluminium electrolytic capacitor of rated voltage similar to the amplifier's power supply voltage. That capacitor will happily survive indefinitely, regardless of whether the amplifier has 'gone DC' or is working correctly. More important it will generate almost no measurable distortion. **Fig. 6.**

All polar aluminium electrolytic capacitors inherently include a reverse polarity diode³ so should an amplifier 'go DC', reverse polarising the capacitor by more than 1 volt, capacitor reverse leakage current increases causing a voltage drop across R7. With \pm 50 volt power supplies and 10k Ω for R7, current cannot exceed 4.8mA. This reverse current may degrade the capacitor which should be replaced during

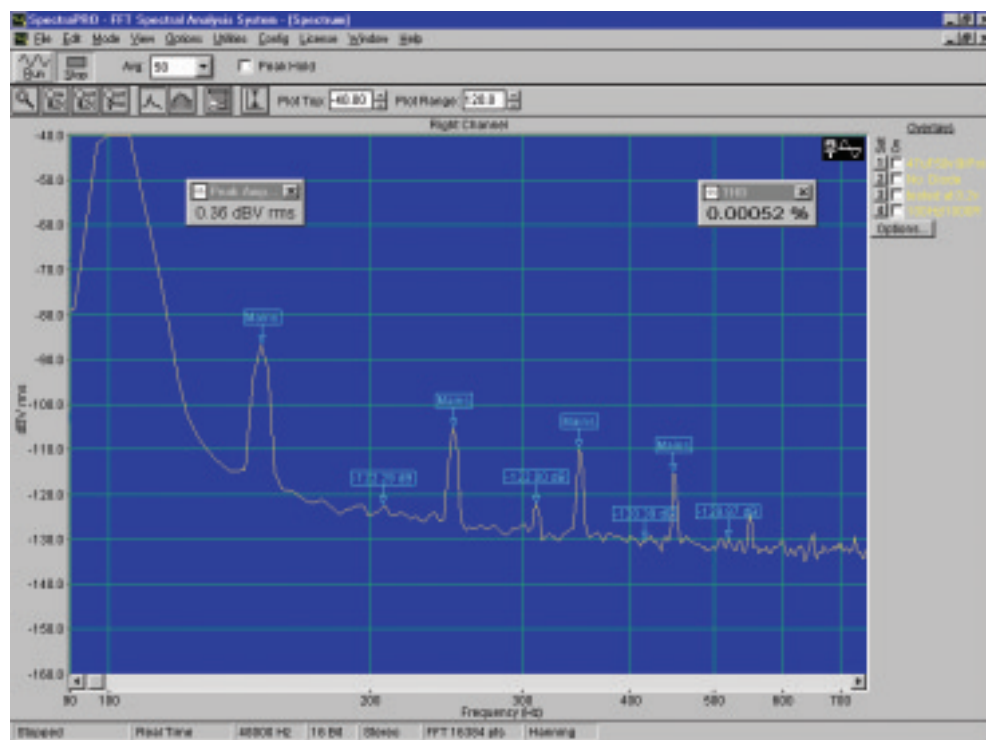


Fig. 6. Without diodes, but otherwise exactly as Figure 5, this Panasonic 'S' 47 μ F 50 volt bi-polar aluminium electrolytic capacitor shows the distortion reduction available by changing a polar capacitor for a bi-polar type. With diodes, third harmonic increased more than 20dB to -99.24dB, further proof of the diode effect.

repair, but is most unlikely to result in capacitor failure.

Zobel circuit

Many designers have expressed concern to me about the output stage CR Zobel network, that the signal voltage across resistor R15 with this resistor's voltage coefficient might generate audible distortion. With C7

and R15 already modelled, we can quickly explore this Zobel network.

With typical component values of 0.1 μ F and 4.7 to 10 Ω , the 0.1 μ F capacitor sustains almost all the amplifier output voltage at least to 10kHz and is more highly stressed than the resistor. At higher frequencies, resistor voltage increases but capacitor voltage reduces little.

Technical support

Full details of the 'Real Time' hardware test method and my original *Capacitor Sounds* low distortion oscillator, buffer amplifier, notch filter/preamplifier and DC bias assemblies, complete with parts lists, assembly manuals and full size printed circuit board drawings, as .PDF files arranged for easy viewing of the figures, on screen or hardcopy, are provided in my CD.

This CD includes updated and much expanded re-writes with very many more figures, of my first series *Capacitor Sounds* articles, supported now by some ninety capacitor distortion measurement plots as well as articles from this new *Capacitor SoundsII* series.

Also included are PDF re-writes of my earlier *Understand Capacitors* series together with articles on how to diagnose failed printed board mounted capacitors and essential low cost capacitor measurement methods, more than twenty popular articles.

This CD costs £15 Sterling inclusive of post & packing.

I can also supply sets of three professionally manufactured printed circuit boards, FR4 with legend and solder resist also four gang potentiometers, as described in my original *Capacitor Sounds* articles.

One set of boards costs £27.50 but due to weight, post and packing is extra.

Four gang potentiometer if ordered together with PCBs costs £5.00.

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